THE RESPIRATORY GASES

GAS EXCHANGE AND TRANSPORT

The mechanics of breathing in respiration involve pulmonary ventilation—the constant replacement of fresh air into the lungs (discussed in Chapter 17). The first phase in the respiratory cycle is the movement of oxygen from the alveolar air to the blood and the movement of carbon dioxide in the reverse direction. The blood leaves the lungs low in carbon dioxide and saturated with oxygen. The second phase occurs in the capillary walls throughout the body. Again, there is the movement of the respiratory gases: Oxygen diffuses out of the blood into the cells and carbon dioxide passes from the cells into the blood.

Diffusion of Gases into the Blood

On entering the blood, both oxygen and carbon dioxide form simple solutions in the plasma. Since there is a limit to the amount of gas that can dissolve in a given volume of a plasma (Henry's law), some oxygen and carbon dioxide combine chemically with other components of the blood.

Representations of these essential physical processes and chemical reactions are shown in Fig. 18-3 and 18-4. Several important facts are illustrated to assist in understanding the basic principles of gas transport. In Figure 18-3 the reactions proceed in a clockwise direction. As oxygen diffuses from its area of highest partial pressure (the alveolus) into an area of lower pressure (the plasma and the red blood cells), carbon dioxide simultaneously diffuses from its area of highest partial pressure (the blood) into an area of lower pressure (the alveolus) for exhalation.

In Fig. 18-4, carbon dioxide diffuses from its area of greatest partial pressure (the tissue cell) into an area of lower pressure (the plasma and red blood cells) for transport to the lung. If you follow the reactions in a counterclockwise direction, you will note the simultaneous diffusion of oxygen from its area of greatest partial pressure (the red blood cell) into an area of lower pressure (the tissue cell). In comparing the two figures, the conditions that have changed are the partial pressures of the gases and the place where gas exchange occurs. In the lung, oxygen is entering the blood while carbon dioxide is leaving. In the tissue cells, carbon dioxide moves into the blood while oxygen is leaving.

Oxygen transport. The amount of oxygen that dissolves in the plasma is extremely small. Approximately 0.5 ml of oxygen will dissolve in every 100 ml of blood. However, there is actually about 20 ml of oxygen in every 100 ml of blood. This additional amount of oxygen chemically combines with ***hemoglobin (Hb)***, the protein in red blood cells. Hemoglobin has the ability to combine chemically with oxygen to form ***oxyhemoglobin:***

$$Hb + O_2 \rightleftharpoons HbO_2$$

One gram of hemoglobin can unite with approximately 1.3 ml of oxygen. With 15 grams of hemoglobin in 100 ml of blood, 20 ml of oxygen can be carried. This is more than the 0.5 ml of oxygen that is carried in the plasma. Hemoglobin that has lost its oxygen-carrying capacity is called *reduced hemoglobin* and can lead to a condition called ***hypoxia.***

Carbon dioxide transport. Carbon dioxide diffuses from the tissues into the blood. Most of the carbon dioxide enters the red blood cells, with a small amount remaining in the plasma. Of this carbon dioxide in the plasma, some is carried in simple solution and some combines with water to form carbonic acid:

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \rightleftharpoons \underset{\text{carbonic acid}}{H_2CO_3} \rightleftharpoons \underset{\text{hydrogen ion}}{H^+} + \underset{\text{bicarbonate ion}}{HCO_3^-}$$

Carbonic acid, if produced in large amounts, lowers the pH of the blood. ***Buffers*** are substances found in a solution that can prevent the accumulation of hydrogen ions (H^+). Since this reaction is not catalyzed by any enzyme, it is very slow and the free hydrogen ions are quickly ***buffered*** by the *plasma buffer systems.*

Acid-base balance. The major buffering of carbon dioxide occurs within the red blood cells. Within these cells is a special enzyme called ***carbonic anhydrase.*** This enzyme speeds up the reaction of carbon dioxide with water so that large quantities of carbonic acid are formed. Hemoglobin then serves as a buffer by combining with the excess hydrogen ions, thus preventing their accumulation in the blood plasma. The reaction can be written as follows:

$$\underset{\text{hemoglobin}}{Hb} + \underset{\text{hydrogen ions}}{H^+} \longrightarrow \underset{\text{reduced hemoglobin}}{HHb}$$

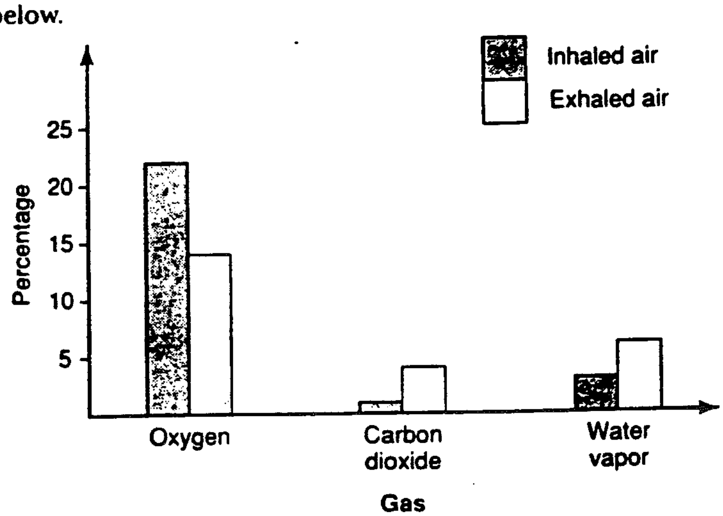
The large numbers of negative bicarbonate ions (HCO_3^-) resulting from the rapid formation of carbonic acid diffuse rapidly through the cell membrane of the red blood cell. As a result, the interior of the cell loses its electrical neutrality. To reestablish the electroneutrality of the interior of the cell, negative chloride ions (Cl^-) in the plasma move to the interior of the red cells. This exchange of Cl^- for HCO_3^- is called the ***chloride shift.*** The process is reversed when blood reaches the lungs. (See Figs. 18-3 and 18-4.)

Carbon dioxide is also carried in combination with hemoglobin and forms a compound called ***carbaminohemoglobin*** ($HHbCO_2$). Thus hemoglobin functions to carry oxygen to the tissues and aids in the removal of carbon dioxide from the tissues.

hem = blood

Graphing Data

A chemical analysis of the gases that are inhaled and exhaled is illustrated in the graph below.



1. Based on the graph, describe what happens to the air that is inhaled.

____

____

____

2. Where in the respiratory system does each of the events described in your answer to question 1 occur? ____

____

____

____

1. How is oxygen carried in the blood?

2. How is carbon dioxide carried in the blood?

3. What happens in carbon monoxide poisoning?

Hyperventilation. As individuals are exposed to conditions found above 3 kilometers (10,000 feet), a series of physiological reactions occurs as the body tries to maintain homeostasis under new and, in this case, adverse conditions. The first visible response is ***hyperventilation,*** or an increase in the rate and depth of breathing, as the body tries to acquire more oxygen. There is also an increase in the numbers of red blood cells released from storage areas, such as the spleen. This increases the total hemoglobin content and thus the oxygen-carrying capacity of the blood. The hyperventilation eliminates (by exhalation) an excessive amount of carbon dioxide and thus decreases the level of carbonic acid, which means that the hydrogen ion concentration of the plasma is also reduced. When the arterial p_{CO_2} is lowered, ventilation decreases. The decrease in breathing rate (lowering the H^+ concentration) raises the pH of the blood, but the kidneys restore the plasma pH to its normal level.

hyper = excess

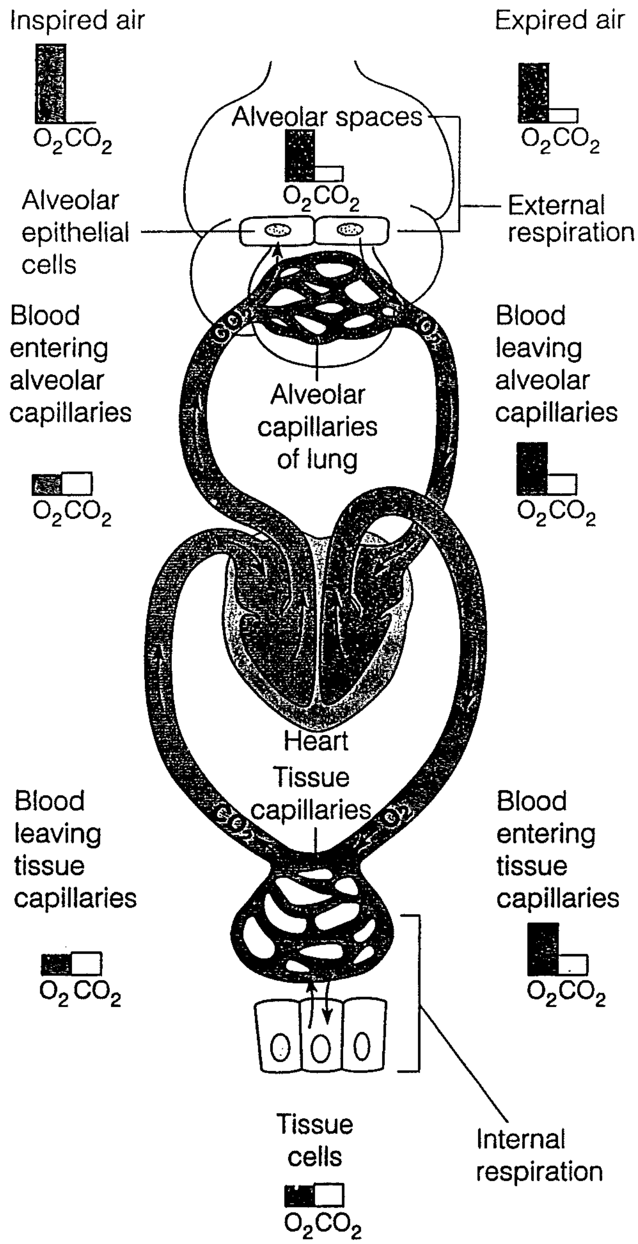


Figure 13.10 Gas exchanges in the body occur according to the laws of diffusion.

SKILL ACTIVITY—
Applying concepts

Understanding the Physics of Respiration

Exactly how is oxygen carried from the lungs to the body tissues? How is carbon dioxide carried from the body tissues to the lungs? In this activity, you will use some simple principles of physics to understand and explain this exchange of oxygen and carbon dioxide.

According to Dalton's Law of partial pressures, each gas that is part of a mixture of gases exerts its own pressure as if all the other gases in the mixture were not present. This kind of partial pressure is referred to by the abbreviation *p*. The partial pressure of oxygen, therefore, would be written pO_2.

Atmospheric air is a mixture of several gases, including nitrogen, oxygen, carbon dioxide, and water vapor. Atmospheric pressure, like the pressure of any gas, is measured by the height of the column of mercury that it can support. A standard is established by comparing the heights of mercury at different pressures. Average atmospheric pressure can support a column of mercury (Hg) that is 760 mm high.

The partial pressure of each gas in a mixture can be calculated by multiplying the percentage of the gas present in the mixture by the total pressure of the gas. For example, to find the partial pressure of oxygen, which makes up 21 percent of atmospheric air, multiply 21 percent (.21) by the total atmospheric pressure, 760 mm Hg. Fill in the table after you have calculated the partial pressure of each gas present in air.

CALCULATING PARTIAL PRESSURES OF ATMOSPHERIC AIR

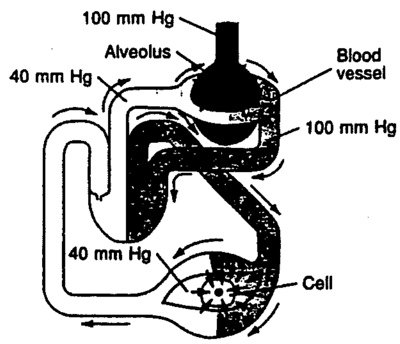
Gas	Percent of Air	Partial Pressure
O_2	21	$.21 \times 760$ mm Hg = 160 mm Hg
N_2	79	
CO_2	.04	

Before atmospheric air reaches your lungs, it is warmed and moistened by the nasal passages and bronchi. Therefore, air in your lungs is warmer and has more water than atmospheric air. Warming and moistening atmospheric air decreases the partial pressures of each gas. Inside the alveoli, the partial pressure of oxygen is 100 mm rather than 160 mm.

© Prentice-Hall, Inc.

Now consider the gas exchange inside and outside the lungs and body cells. Look at Figure 1. It shows what oxygen transport would be like if blood contained only plasma and no red blood cells.

Figure 1



Gas transport as if red blood cells were not present, that is, the transport of gases by the blood plasma

1. What is the partial pressure of oxygen (pO_2) in the alveolus? ____________________
2. Explain why the pO_2 that has left the alveolus and is now in the plasma is the same as the pO_2 in the alveolus. ____________________

   ____
3. What is the pO_2 in the plasma after the O_2 leaves the body cell? ____________________

   ____
4. Explain why the pO_2 that has left the body cells and entered the plasma is less than the pO_2 in the plasma before it has entered the body cells.

   ____

   ____
5. Explain why oxygen diffuses from the alveolus into the plasma that surrounds the body cells.

   ____

   ____

If plasma alone can transport O_2 and CO_2 in this fashion, why does the body need red blood cells? To answer this question, you must first understand the difference between partial pressure and solubility, or the capability of a gas to dissolve in a liquid such as plasma. Pressure is a force caused by the movement of molecules. Solubility refers to the number of molecules that can dissolve in a liquid. Oxygen is only slightly soluble in plasma. Notice that in Figure 1, the pO_2 in the lungs is equal to the pO_2 in the plasma that has left the lungs. The plasma, however, contains fewer molecules of oxygen than those contained by the lungs. The plasma has absorbed all that it can at a pO_2 of 100 mm Hg. If any more O_2 were dissolved in plasma, the same amount of O_2 would be released from the plasma. The pO_2 in the plasma and pO_2 in the air in the alveoli would be equal.

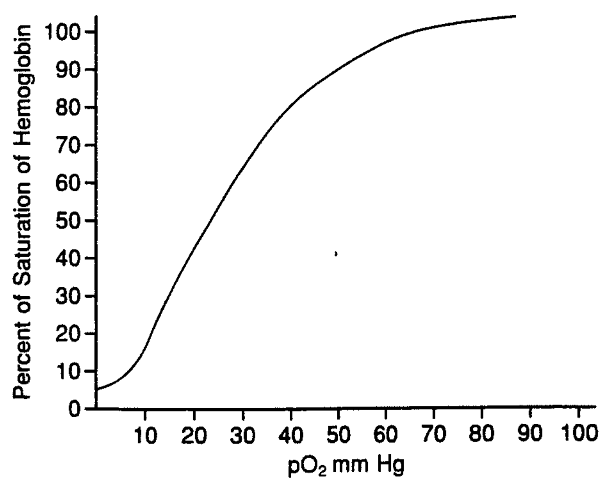
© Prentice-Hall, Inc.

Plasma alone cannot supply the body cells with all the oxygen they need. Suspended in plasma are red blood cells that are attracted to oxygen. In red blood cells, the hemoglobin combines chemically with dissolved oxygen in the blood.

6. What happens to the pO_2 in the blood when oxygen combines with hemoglobin?

Because of the presence of red blood cells, 100 mL of blood leaving the lungs contains 20 mL of oxygen. What happens when the red blood cells reach the body cells? Why do red blood cells give up their oxygen? The chemical reaction that combines O_2 with hemoglobin is completely reversible. The percentage of hemoglobin that is combined with O_2 depends on the pO_2 in the plasma. Examine the graph, which shows the percent of hemoglobin saturation at different pO_2 in plasma.

7. If the pO_2 in the plasma that surrounds the body cells was 55 mm Hg, what percent of hemoglobin would be saturated?



8. Examine the graph. What happens to the percent of hemoglobin saturation when the pO_2 decreases?

---

9. What happens to the oxygen in the red blood cells when the pO_2 in the plasma decreases?

© Prentice-Hall, Inc.